THE U.S. U-235 FISSION SPECTRUM STANDARD NEUTRON FIELD REVISITED

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ABSTRACT

As use is made of a standard neutron field, formerly unidentified needs and ways to improve its performance became apparent. This paper presents improvements in calibration techniques, results of Monte Carlo calculations which better define scattering corrections, and new handling procedures which improve reproducibility and decrease radiation exposure to personnel. Also, an application of the NBS ^{235}U fission spectrum to test consistency among laboratories who analyze surveillance dosimetry for reactor pressure vessel exposures is summarized.

NBS ^{235}U CAVITY FISSION SOURCE IRRADIATION FACILITY

The U.S. standard ^{235}U fission neutron spectrum at the National Bureau of Standards in Gaithersburg, Maryland, operates in the center of a 30-cm diameter spherical cavity located in the graphite thermal column of the NBS Research Reactor. The facility is frequently called the Cavity Fission Source (CFS). The upper view in Figure 1 shows, in detail, the CFS assembly[1] containing neutron sensors and the lower view shows its location within the thermal column cavity. Two disks of ^{235}U metal (16-mm dia x 0.13-mm thick) are placed above and below a cylindrical cadmium pill box 0.076-cm thick, which encloses approximately six passive neutron sensors (nomimally 1.27-cm diameter x 0.025-cm thick). The neutron sensors to be irradiated are held in the center of the assembly by light-weight aluminum pieces.

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Fission fluence rates of ~2 x 10^{10} $n/cm^2 \cdot s$ are obtained between the ^{235}U source disks at a separation distance of one centimeter. Applications include detector calibrations for reactor dosimetry and fission cross section measurements.

The absolute source strength, and therefore the fluence rate, of the CFS is dependent upon reactor power level. Consequently, a fluence monitor that is independently calibrated is required for each irradiation. Both the 70.8-day $^{58}Ni(n,p)^{58}Co$ reaction and the 4.5-hr $^{115}In(n,n')^{115m}In$ reaction together with a fission-chamber or a power-level monitor have been used. The CFS fluence is tied through these monitors back to known ^{252}Cf fission neutron fields.

^{252}Cf Standard Neutron Fields at NBS and Their Calibrations

The source for the NBS ^{252}Cf spontaneous fission neutron field is a bead of $^{252}CfO_2$ in a light-weight aluminum and stainless steel capsule. The source is suspended 1.6 m from the nearest reflecting surface in a low-scatter environment. The free-field fluence rate for such a ^{252}Cf source is then a function of only source strength, source-to-detector distance, time, and appropriate geometry-dependent scattering corrections.

All neutron fluence scales in NBS standard neutron fields are traceable to NBS-I, the national standard, radium-beryllium, photoneutron source. The most recent calibrations of its source strength were made in 1961 and 1978[2]. The calibrations agree to within 0.25%. The 4π neutron emission rate of ^{252}Cf fission sources is determined in a 1.2 m diameter, manganous-sulfate bath by comparing induced ^{56}Mn activity with that of NBS-I. This technique is capable of yielding a ^{252}Cf source strength with an uncertainty of ±0.9%.

As mentioned, the ^{252}Cf field is used as an intermediate step in maintaining traceability of other NBS neutron fields to NBS-I. The procedure to accomplish this is known as neutron "fluence transfer."

Fluence Transfer

In the fluence transfer technique, a neutron sensor response is measured first in a standard neutron field and then in the field to be calibrated. For example, transfer from a ^{252}Cf standard neutron field to the NBS ^{235}U CFS has been accomplished by the $^{115}In(n,n')^{115m}In$ reaction. Foils of known purity are irradiated to a certified fluence in the californium field. The indium foils are then analyzed with a radioactivity detector having a reproducible geometry. The factor Φ_{Cf}/R_{Cf} ($n \cdot cm^{-2}$ per counts$\cdot s^{-1} \cdot gm^{-1}$) is thereby established for the neutron sensor.

Here R_{Cf} could refer to any reproducible response such as counting rate, reaction rate, or fission rate in the field of interest.

The same indium neutron sensor, or a different indium sensor with a known mass, is then exposed to a certified fluence in the ^{235}U field and the desired fluence , Φ_{235_U} is given by:

$$\Phi_{235_U} = \frac{\Phi_{Cf}}{R_{Cf}} \cdot R_{235_U} \cdot \frac{\bar{\sigma}_{Cf}(In)}{\bar{\sigma}_{235_U}(In)} \qquad (1)$$

The spectrum-averaged, cross-section-ratio term on the extreme right of Eq. (1) is more accurately known than the cross sections themselves because errors in the scalar magnitudes are eliminated by the division. For the $^{115}In(n,n')^{115m}In$ reaction, the cross section ratio has been calculated to be 1.048 ±1.6%, using ENDF/B-V differential cross section data and the NBS evaluations of the ^{252}Cf and ^{235}U fission spectra. However, different analytical forms of the ^{235}U spectrum give calculated ratios which are as small as 1.015. The experimental value for the ratio is 1.031 ±2.1%.[3] To circumvent this uncertainty in the fluence transfer process, the $^{239}Pu(n,f)$ reaction has replaced In(n,n') for fluence transfer based upon new experiments performed at a ^{235}U cavity fission source in Mol, Belgium.[3] For ^{239}Pu, the spectrum-averaged cross section ratio is 1.003 ±0.2%, with only a 0.3% uncertainty resulting from different descriptions of the spectra.

Fluence Transfer Through the Belgian ^{235}U Fission Spectrum

Fig. 2 shows the ^{235}U cavity fission source assembly at the SCK/CEN Laboratory, Mol, Belgium.[4] This assembly incorporates a 100-cm dia. cavity as opposed to the 30-cm dia. cavity for the NBS ^{235}U field. The significance of the larger cavity is that there are substantially fewer low-energy (wall returned) neutrons in the Belgian field. Also, the larger source permits exposure of high quality, light-weight ^{239}Pu deposits in an NBS fission chamber. This chamber cannot be used in the smaller volume NBS Cavity Fission Source.

Fig. 3 depicts the present and former (indium "only") fluence transfer procedures from the NBS ^{252}Cf fission spectrum. With the exception of differences in the scattering corrections in the Belgian and NBS ^{235}U fields, their energy spectra are identical. Therefore, details of the cross section of the reaction chosen as the transfer instrument do not matter (see Eq. 3 at bottom of Fig. 3). Scattering differences in the two fields require a net adjustment of almost 4%; however, this correction has been calculated to ±1.4%.

Tables I and II summarize the uncertainties in the fluence transfer process. The total uncertainties for In(n,n') and for ^{58}Ni(n,p) are the uncertainties of Tables I and II taken in quadrature. Respectively, these are 2.0% and 2.3%.

Neutron Scattering and Removal Effects

Corrections must be made for effects of neutron scattering and removal because of the variety of materials in close proximity to each neutron sensor undergoing irradiation in a cavity fission source. For example, there are cadmium, aluminum in support structures, uranium in the fission disks, and various elements in other dosimeters. The corrections are a complex function of the cross sections (or thresholds) of the dosimetry reactions as well as the position of a particular sensor relative to all other materials. The present corrections for the NBS CFS are based upon rather extensive Monte Carlo calculations* of indium, nickel and aluminum dosimeters in a detailed model of the cavity fission source. The results are summarized in Fig. 4.

INTRALABORATORY CONSISTENCY OF RADIOMETRIC SENSOR ANALYSES

Between July 1978 and March 1979, twenty-seven nickel foils were irradiated in the NBS ^{235}U CFS, activating the ^{58}Ni(n,p)^{58}Co reaction. Subsequently, the relative foil activities were measured at NBS and then most were distributed internationally to test consistency among laboratories that frequently analyze radiometric dosimeters.

Results were submitted by eighteen laboratories. A number of factors made a direct comparison of fluence measurements difficult:

(1) Although a standard reporting form was distributed, some participants reported only ^{58}Co activity. Also, several laboratories submitted more than one result, from either measurements on multiple gamma counters or from an exchange of foils with some other participant.

(2) To ease the "burden" of having to calculate a spectrum-averaged cross section, the value of 102 mb was also distributed. This value was obtained by integrating ENDF/B-V data over the NBS evaluation of the ^{235}U fission spectrum. Many participants preferred to calculate and use their own cross section getting values up to 111 mb. The current experimental value is 110 ±2.5%.[2]

(3) Complex scattering corrections (up to ~2% in magnitude) could not be made until lengthy Monte Carlo calculations were completed.

*The calculations were performed by Dr. P. Sorenson at the Los Alamos Scientific Laboratory.

(4) The results from the indium fluence-rate monitors were discovered to be uncertain to ~2% because of flux variations due to reactor shim-arm movements which effect gradients in the thermal column but were not evident from the reactor power history charts.

To directly intercompare activity measurement capability, the ratio of the reported activity to the NBS-measured relative activity was determined. The results are shown in Fig. 5. The error bars are those reported by the laboratory, if available, or an arbitrarily assigned ±2%, if not. The mean value of the measurements is shown with an associated ±2% inner band. The outer lines show the actual standard deviation of ±4.7%. The largest difference from the mean is 12%. The associated laboratory requested a second nickel foil which when analyzed agreed with the NBS measurement to ~3%. The large discrepancy was never resolved. A final report on the NBS fluence values for the individual nickel foils must still be sent to the participants. A less accurate comparison of fluence results was published in Ref. 5 in 1982.

REFERENCES

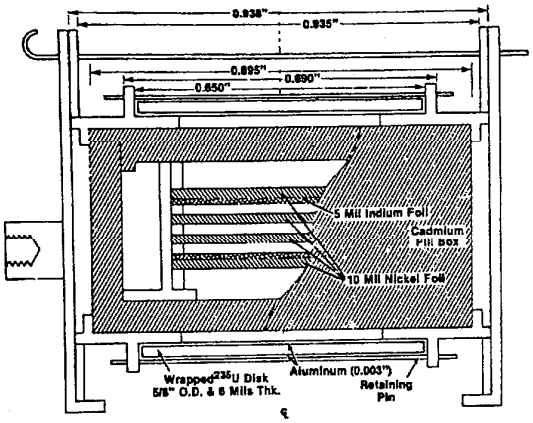
1. Compendium of Benchmark and Test Region Neutron Fields for Pressure Vessel Irradiation Surveillance; Standard Neutron Spectra. NRC NUREG/CR-0551, Progress Report--July-Sept. 1978 (Dec. 1978).

2. "Neutron Fluence and Cross Section Measurements for Fast Neutron Dosimetry," G. P. Lamaze, D. M. Gilliam, E. D. McGarry, NBS, Gaithersburg, Maryland; A. Fabry, SCK/CEN Laboratory, Mol, Belgium; Proc. of Int'l. Conf. Nucl. Meth. and Environ. and Energy Res., San Juan, PR (April 1984) (Proc. to be published by Department of Energy).

3. "Cross Section Measurements in the ^{235}U Fission Spectrum Neutron Field," D. M. Gilliam, J. A. Grundl, G. P. Lamaze, C. M. Eisenhauer, NBS, Gaithersburg, Maryland; A. Fabry, SCK/CEN Laboratory, Mol, Belgium (Sept. 1984). (This ASTM/EURATOM Symposium.)

4. "The Mol Cavity Fission Spectrum Standard Neutron Field and Its Applications," A. Fabry, G. Minsart, F. Cops, and S. DeLeeuw; Proc. Fourth ASTM/EURATOM Symposium on Reactor Dosimetry, Washington, DC (March 1982).

5. E. D. McGarry, "Requirements for Referencing Reactor Pressure Vessel Surveillance Dosimetry to Benchmark Neutron Field" in Nuclear Data for Radiation Damage Assessment and Related Safety Aspects, Proc. of the Advisory Group Meeting, Vienna, Austria, Oct. 12-16, 1981; IAEA-TECDOC-263 (1982).



NBS ^{235}U CAVITY FISSION SOURCE

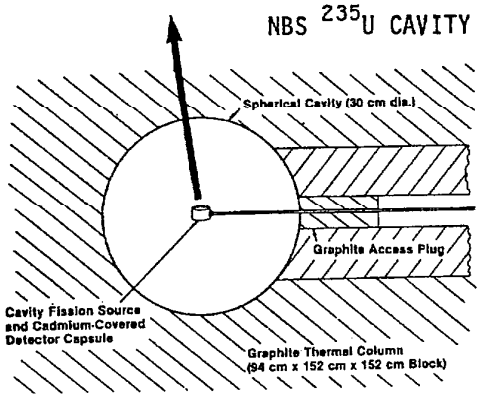


Figure 1.

Belgian (SCK/CEN) ^{235}U Fission Spectrum Field in BR1 Reactor Thermal Column

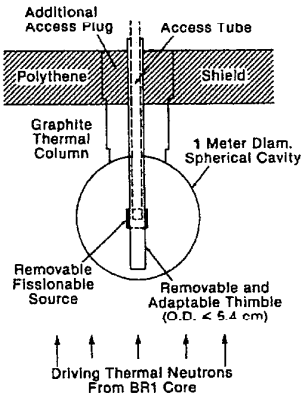


Figure 2.

TABLE I.

Summary Of Uncertainties In Fluence Transfer Measurements

- For Transfer From NBS ^{252}Cf Field to Belgian ^{235}U Field

Source of Uncertainty	Contribution (%)
Source Strength of ^{252}Cf	0.9
^{252}Cf-Source to ^{239}Pu-Deposit Distance	0.6
Statistics of Fission Counting	0.1
Precision of 2π Fission Counting Corrections	0.4
^{239}Pu Cross-Section Ratio in ^{252}Cf Field and ^{235}U Field	0.1
Scattering Corrections for ^{239}Pu in ^{252}Cf Field	0.7
Wall Return Corrections in Belgian ^{235}U Field	0.6
Scattering Corrections for ^{239}Pu in Belgian ^{235}U Field	0.1
Total Uncertainty in Fluence Transfer = (Contributions Taken in Quadrature)	1.5%

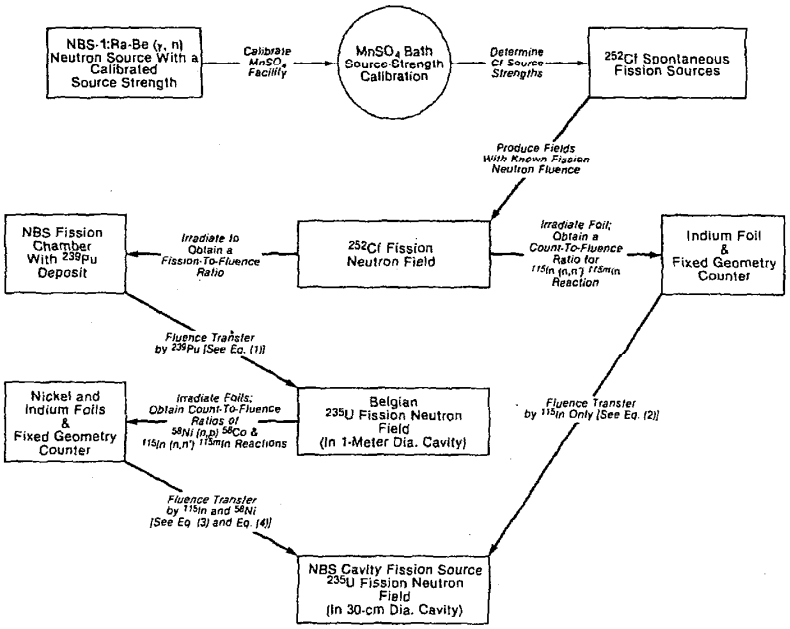
TABLE II.

Summary Of Uncertainties In Fluence Transfer Measurements

- For Transfer From Belgian to NBS ^{235}U Field

Source of Uncertainty	*Contribution (%)*	
	For ^{115}In (n, n')	For ^{58}Ni (n, p)
Statistics of Gamma Counting	0.2	0.4
Scattering + Wall Return in Belgian ^{235}U Field	0.9	1.4
Scattering + Wall Return in NBS ^{235}U Field	0.8	0.8
Fluence-Rate Gradient in NBS ^{235}U Field	0.4	0.4
Total Uncertainty in Fluence Transfer = (Contributions Taken in Quadrature)	1.3%	1.7%

Present and Former Procedures for *Calibration Of* The Neutron Fleunce Rate In The NBS ^{235}U Cavity Fission Source



$$\phi^{SCK/CEN}_{U\text{-}235} = \left[\frac{\phi_{cf}}{F^{Pu\text{-}239}_{cf}}\right] \bullet F^{Pu\text{-}239}_{U\text{-}235} \bullet \left[\frac{\overline{\sigma}^{Pu\text{-}239}_{cf}}{\overline{\sigma}^{Pu\text{-}239}_{U\text{-}235}}\right] \quad (1)$$

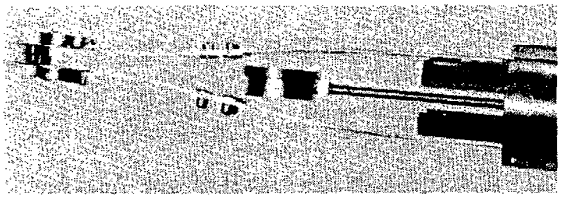
$$^{Old}\phi^{NBS}_{U\text{-}235} = \left[\frac{\phi_{cf}}{R^{In\text{-}115}_{cf}}\right] \bullet R^{In\text{-}115}_{U\text{-}235} \bullet \left[\frac{\overline{\sigma}^{In\text{-}115}_{cf}}{\overline{\sigma}^{In\text{-}115}_{U\text{-}235}}\right] \quad (2)$$

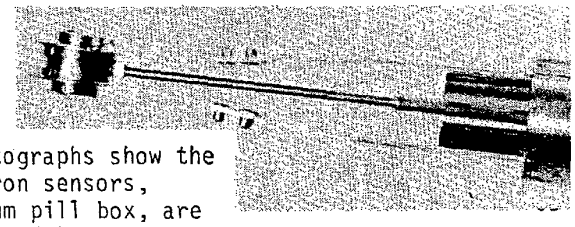
$$^{New}\phi^{NBS}_{U\text{-}235} = \left[\frac{\phi^{SCK/CEN}_{U\text{-}235}}{R^{Ni\text{-}58}_{U\text{-}235\,(SCK)}}\right] \bullet R^{Ni\text{-}58}_{U\text{-}235\,(NBS)} \quad (3)$$

$$^{New}\phi^{NBS}_{U\text{-}235} = \left[\frac{\phi^{SCK/CEN}_{U\text{-}235}}{R^{In\text{-}115}_{U\text{-}235\,(SCK)}}\right] \bullet R^{In\text{-}115}_{U\text{-}235\,(NBS)} \quad (4)$$

Figure 3.

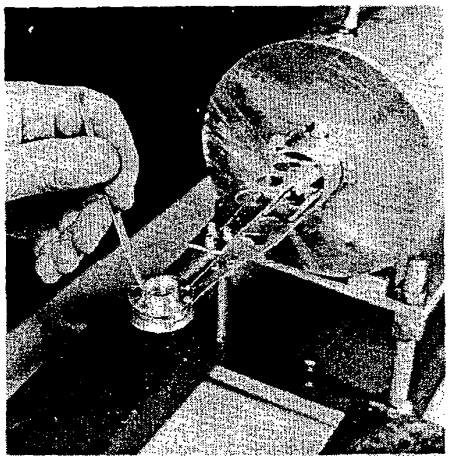
NBS Cavity Fission Source

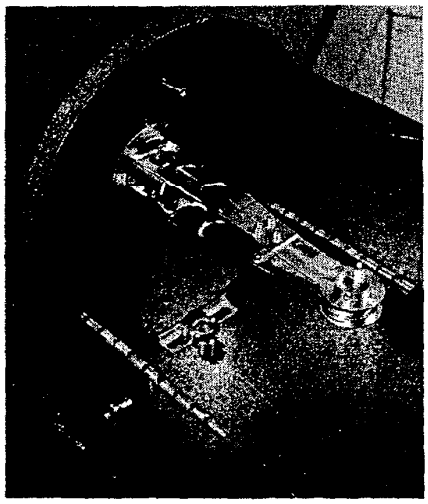




The above two photographs show the way in which neutron sensors, inside of a cadmium pill box, are reproducibly inserted between two highly radioactive fission disks.

The photograph to the right shows "cold" fission disks being mounted. The cylindrical assembly is a lead shield which will be used for their removal after the irradiation.

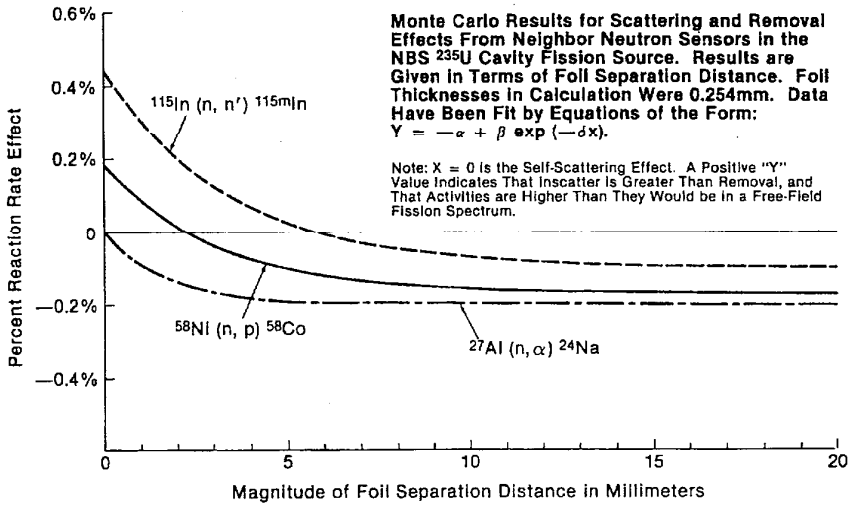




The photograph to the left shows the fission disks and cadmium-covered neutron sensors mounted inside of a graphite cavity, which will be inserted into the thermal column of the NBS Research Reactor.

Improved Handling Mechanism for the NBS Cavity Fission Source

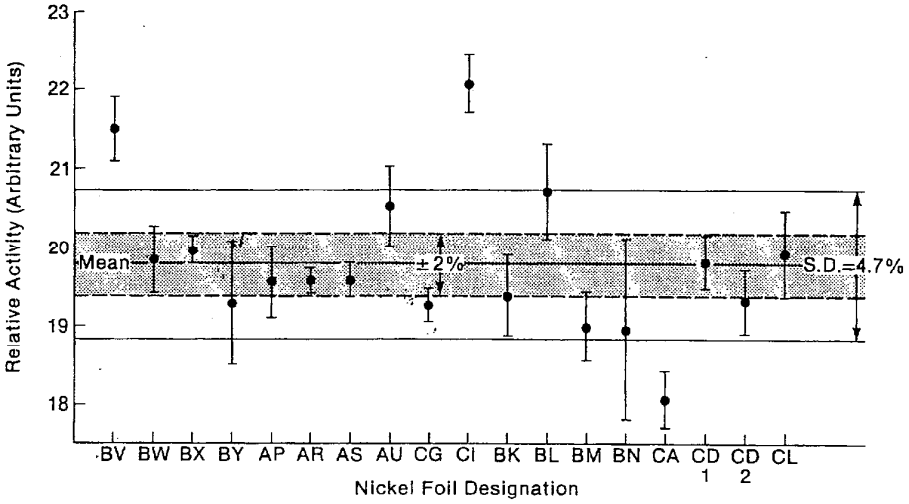
Figure 6.



Monte Carlo Results for Scattering and Removal Effects From Neighbor Neutron Sensors in the NBS ^{235}U Cavity Fission Source. Results are Given in Terms of Foil Separation Distance. Foil Thicknesses in Calculation Were 0.254mm. Data Have Been Fit by Equations of the Form: $Y = -\alpha + \beta \exp(-\delta x)$.

Note: X = 0 is the Self-Scattering Effect. A Positive "Y" Value Indicates That Inscatter Is Greater Than Removal, and That Activities are Higher Than They Would be in a Free-Field Fission Spectrum.

Figure 4.



Results of an intercomparison of activity measurements of the 70.8-day activity from the $^{58}Ni(n,p)^{58}Co$ reaction induced in a certified fluence irradiation in the NBS Cavity Fission Source.

Figure 5.